

# An Approach for Measuring Methane Emissions from Whole Farms

S. M. McGinn,\* T. K. Flesch, L. A. Harper, and K. A. Beauchemin

## ABSTRACT

Estimates of enteric methane ( $\text{CH}_4$ ) emissions from ruminants are typically measured by confining animals in large chambers, using head hoods or masks, or by a ratiometric technique involving sampling respired air of the animal. These techniques are not appropriate to evaluate large-scale farm emissions and the variability between farms that may be partly attributed to different farm management. This study describes the application of an inverse-dispersion technique to calculate farm emissions in a controlled tracer-release experiment. Our study was conducted at a commercial dairy farm in southern Alberta, Canada (total of 321 cattle, including 152 lactating dairy cows). Sulfur hexafluoride ( $\text{SF}_6$ ) and  $\text{CH}_4$  were released from 10 outlet locations (barn and open pens) using mass-flow controllers. A Lagrangian stochastic (LS) dispersion model was then used to infer farm emissions from downwind gas concentrations. Concentrations of  $\text{SF}_6$  and  $\text{CH}_4$  were measured by gas chromatography analysis and open path lasers, respectively. Wind statistics were measured with a three-dimensional sonic anemometer. Comparing the inferred emissions with the known release rate showed we recovered 86% of the released  $\text{CH}_4$  and 100% of the released  $\text{SF}_6$ . The location of the concentration observations downwind of the farm was critically important to the success of this technique.

THE GLOBAL RELEASE of methane ( $\text{CH}_4$ ) from agricultural sources accounts for two-thirds of the anthropogenic  $\text{CH}_4$  sources (Moss et al., 2000). These sources include rice growing, fermentation of feed by ruminants (enteric  $\text{CH}_4$ ), biomass burning, and animal wastes. Globally, ruminant livestock are responsible for about 85 Tg of the 550 Tg  $\text{CH}_4$  released annually. There is, however, considerable uncertainty associated with the estimates of  $\text{CH}_4$  from livestock due to the scant availability of data to document the variability that exists at the farm scale (e.g., due to the significant impact of diet on enteric  $\text{CH}_4$  production). Part of the problem is the difficulty of making emissions measurements from livestock facilities.

A few studies have measured  $\text{CH}_4$  emissions using close approximations to real farms. Kinsman et al. (1995) calculated  $\text{CH}_4$  emitted from a barn housing dairy cows, by monitoring inflow and exhaust air concentration and airflows. However, this technique, aside from being technologically challenging, cannot be applied to the majority of more modern "open" dairy barns or beef feedlots where the airflow is passive. A more appro-

priate approach for open facilities is to release a tracer gas at a known rate (Marik and Levin, 1996; Kaharabata et al., 2000). This assumes the relationship of the tracer flux to the tracer concentration in the downwind plume is similar for that of the target gas (where the concentration is also measured). Although this ratiometric technique is theoretically straightforward, it relies on matching the tracer and target gas sources that can be difficult to achieve (because the true emission configuration is unknown) and requires extensive setup time.

A more flexible technique for quantifying emissions is to model the dispersion of a target gas from the source (e.g., Kaharabata et al., 2000; Flesch et al., 2004), so that a downwind concentration of gas can establish the emission rate. This "inverse-dispersion" technique has the potential advantage of simplicity, as it requires only a single gas concentration measurement and basic wind information. However, most of the applications of this technique have been for emission sources over a uniform surface (e.g., Wilson et al., 1982). For more complex settings, like a farm with buildings and trees, further evaluation of the inverse-dispersion approach is needed.

The objective of our study was to examine the application of an inverse-dispersion technique that could be easily deployed to determine farm-scale  $\text{CH}_4$  emissions (or any other trace gas). Such a technique would allow the quick evaluation of mitigation practices of entire farms and provide a means of understanding the variability that exists between different farm types.

## MATERIALS AND METHODS

### Study Site

The study was conducted at a commercial dairy farm (49°48' N, 112°22' W) near Lethbridge, Alberta, where cows were located in an open pen (total area 9560 m<sup>2</sup>) and a large barn (stall area 7680 m<sup>2</sup>) (Fig. 1). The upper half of the barn walls were curtains that opened and closed depending on air temperature in the barn. These curtains were opened during the daytime allowing natural ventilation of the barn air. The peak of the barn roof (approximate 8-m height) was opened allowing natural air exchange as well. Manure within the barn was scraped from the floor daily and stored in tanks below floor level. These holding tanks were periodically pumped to an open manure-holding facility located 200 m south of the buildings. Of the 321 cattle at this dairy farm, 152 were lactating cows, 48 were dry cows or heifers over 2 yr, 90 were heifers or steers between 1 and 2 yr, and 31 were heifers or steers less than a year.

The study site was set up between 5 Nov. and 10 Dec. 2004, during which time the alfalfa (*Medicago sativa* L.) fields surrounding the farm were dormant. Except for the farm buildings (highest was the barn at about 8 m) and a small shelterbelt

S.M. McGinn and K.A. Beauchemin, Agriculture and Agri-Food Canada, P.O. Box 3000, Lethbridge, AB, Canada T1J 4B1. T.K. Flesch, Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada T6G 2E3. L.A. Harper, Agricultural Research Service, United States Department of Agriculture, Watkinsville, GA 30677. \*Corresponding author (mcginn@agr.gc.ca).

Published in J. Environ. Qual. 35:14–20 (2006).

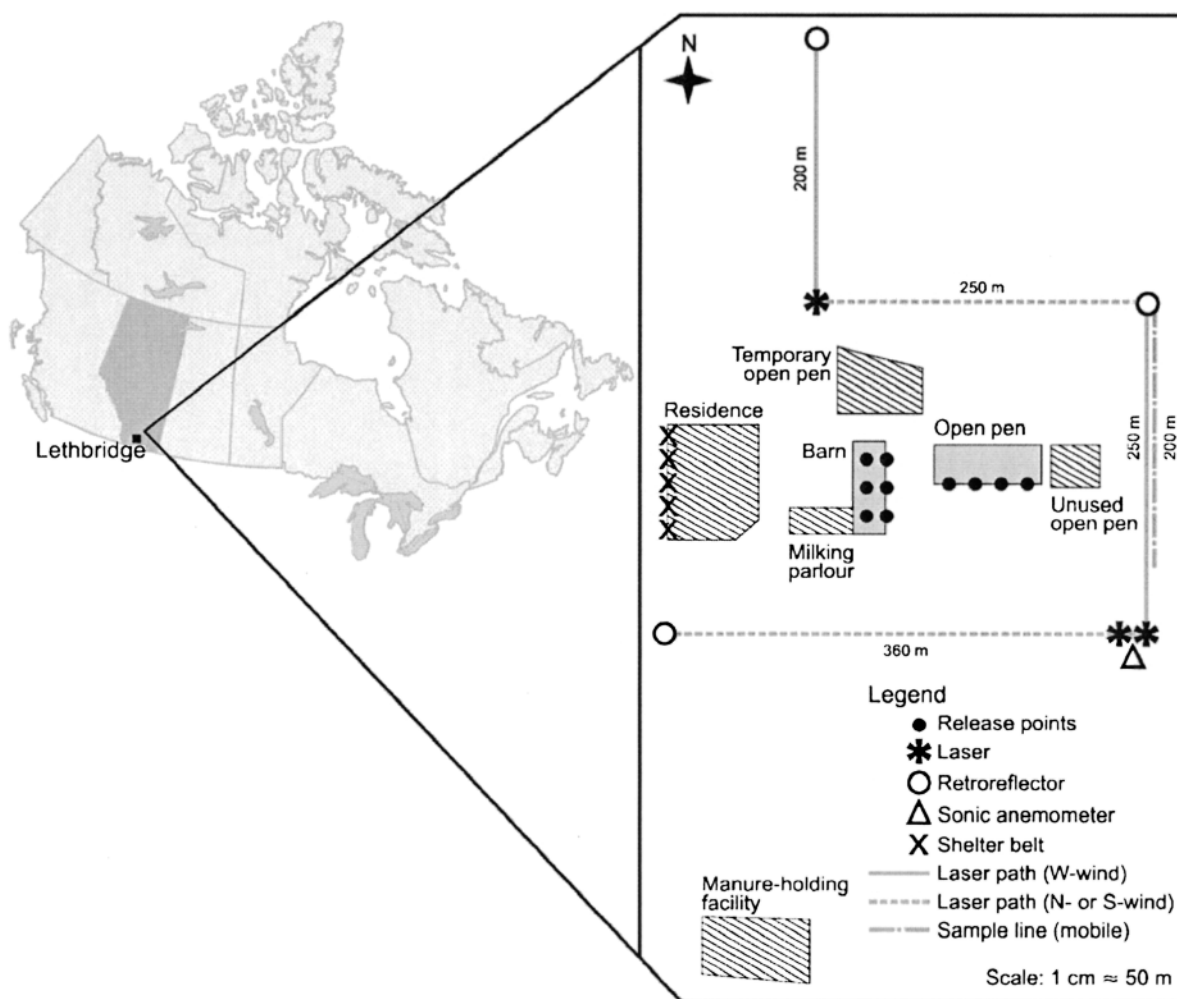
Technical Reports: Atmospheric Pollutants and Trace Gases

doi: DOI: 10.2134/jeq2005.0250

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677 S. Segoe Rd., Madison, WI 53711 USA

**Abbreviations:** (C/F)<sub>sim</sub>, theoretical ratio of concentration to emission; (F<sub>area</sub>/F<sub>point</sub>), ratio emissions based on area to that based on point configure of source; GC, gas chromatograph; h, obstacle height; LS, Lagrangian stochastic; x<sub>ss</sub>, source separation distance.



**Aerial view of the study site showing the position of the barn and open pens housing cows, the release points for  $\text{CH}_4$  and  $\text{SF}_6$ , and the laser and sample lines. The laser in the northwest corner was turned to a north or east reflector depending on wind direction.**

of trees (approximately 8–10 m high) near the farm house (Fig. 1), the surrounding landscape was flat and bare. There were no other livestock facilities for several kilometers in any direction.

### Measurements

Three open-path lasers (GasFinder2; Boreal Laser, Spruce Grove, AB, Canada), tuned for detecting average  $\text{CH}_4$  concentration along a path (1 m above the ground), were situated 75 to 100 m away from the nearest farm building (Fig. 1). Lasers were aligned to enclose the north, east, and south perimeters of the farm; an array of retroreflectors terminated the laser path. When wind direction was westerly, the laser along the north perimeter was turned to a second array of retroreflectors located 200 m to the north of the laser (Fig. 1). In this manner, with minimum effort, there was always one laser recording concentration of the target gas upwind of the farm (background concentration) and one recording downwind (plume) concentration. The average concentration along the laser path was scanned approximately every 5 s and averaged every 15 min. Laser correction factors were determined repeatedly throughout the experiment. When possible we adjusted each laser to match our gas chromatograph (GC) measured  $\text{CH}_4$  concentrations (see below), if the wind direction indicated both the laser and GC samples measured the same

concentration (i.e., background). These corrections varied from 0.83 to 0.97. These corrections were needed to remove bias instrument error that was evident when the three lasers were set side-by-side (2-m separation) in the field with no obvious upwind source. This side-by-side comparison resulted in average  $\text{CH}_4$  concentrations of  $1488 (\pm 93)$ ,  $1560 (\pm 99)$ , and  $1593 (\pm 112) \mu\text{g m}^{-3}$ , which were significantly different from each other ( $P < 0.05$ ). Accuracy analysis (Allen and Raktue, 1981) was used to decompose the differences. On average, this analysis attributed 80% to bias (offset), 13% to random, and 7% to regression error. Assuming nothing changed for the on-farm study, the corrections to the lasers using the GC data removed the largest (bias) error. According to the laser specifications, the accuracy of the laser is  $661.2 \mu\text{g m}^{-3}$  per m (at  $20^\circ$  and 101 KPa), or 3.3 and  $1.8 \mu\text{g m}^{-3}$  over path distances of 200 to 360 m used in our study, respectively. However, our experience suggests that when working with lasers with different histories, and at the low concentrations associated with on-farm  $\text{CH}_4$  plumes, it is necessary to revisit the between-laser precision for each new study. We estimate in our case that maximum differences between lasers from the side-by-side comparison were  $79 \mu\text{g m}^{-3}$ , but during our on-farm study these differences were most likely closer to  $20 \mu\text{g m}^{-3}$  after correcting for bias using the GC data as a common reference.

The average alongwind horizontal velocity ( $U$ ); average wind direction (dir); the standard deviation of alongwind,

acrosswind, and vertical velocity fluctuations ( $\sigma_u$ ,  $\sigma_v$ , and  $\sigma_w$ , respectively); friction velocity ( $u^*$ ); surface roughness ( $z_o$ ); and the Monin–Obukhov stability length ( $L$ ) were calculated from data collected at 10-Hz sampling interval (CR23X datalogger; Campbell Scientific, Logan, UT) using a three-dimensional sonic anemometer (CSAT3; Campbell Scientific). These statistics were calculated following Flesch et al. (2004), using the same 15-min averaging period as for gas concentrations. The anemometer was located at the laser locations in the southeast corner of the farm (Fig. 1). At this location, the influence of the farm buildings was deemed to be far enough away to have minimal impact on the sonic data.

Additional line-averaged concentrations of  $\text{CH}_4$  and sulfur hexafluoride ( $\text{SF}_6$ ) were measured downwind of the farm by drawing air through regulated intakes (using flow-holder valves) every 20 m along a long polyethylene tube (0.6-cm i.d.) at a 1-m height. On 18 November the sample line was lengthened from 100 m (5 intakes) to 200 m (10 intakes) long. A 12-vdc pump (TD3LS7; Brailsford and Company, Rye, NY) was connected to one end of the sample line. The flow rate through each intake was adjusted to be equal and approximately  $2 \text{ L min}^{-1}$ . A 2-L polyethylene bottle was connected to the exhaust of the pump to provide a 1-min time filter. A 20-mL air sample was taken every 5 min using a syringe and septum port. The content of the syringe was immediately discharged into an evacuated vial (6.8 mL volume) through a double septum cap (follows from Rochette and Bertrand, 2003), and the time and date recorded on the vial. Every 30 min, the background concentration upwind of the farm was sampled using three air samples drawn at 1.5-m height with a 20-mL syringe (after purging the syringe three times between sampling). At the end of each day, the vials were taken to the laboratory for analysis of  $\text{CH}_4$  and  $\text{SF}_6$  concentrations on a GC the following day (within 24 h of sampling). The over pressured vial provided a sufficiently large air volume to pass through the electron capture detector (ECD) column in the GC.

Before the start of the experiment, two lines of high-density polyethylene tubing (6-mm i.d.) were laid out to allow independent release of  $\text{SF}_6$  and  $\text{CH}_4$  from 10 release points throughout the barn and pen areas (Fig. 1). The release lines were connected to mass-flow controllers and cylinder tanks of ultrapure  $\text{SF}_6$  and  $\text{CH}_4$ . The gas flow at each release point was adjusted using flow hold valves to be one-tenth of the gas flow set by mass-flow controller, where the mass-flow controller was  $0.2 \text{ L min}^{-1}$  for  $\text{SF}_6$  (GFCS-011806; Aalborg Instruments and Controls, Orangeburg, NY) and  $54.2 \text{ L min}^{-1}$  for  $\text{CH}_4$  (GFCS-011246; Aalborg Instruments and Controls). For each gas, three release points (20 m from each end and at the middle) were located 1 m above the peak of the roof. There were also three release points on the east side of the barn along the ventilation openings (aligned with roof locations). Four release points (2-m height) were spaced along the south perimeter of the open pen that housed the pregnant, nonlactating cows. The mass-flow controller units were checked in the laboratory by releasing gas over a long period of time and measuring the mass loss of the cylinder.

### Emission Calculations

We used the inverse-dispersion technique outlined by Flesch et al. (2004). A Lagrangian stochastic (LS) model predicts the theoretical ratio of the targeted gas concentration to the emission rate  $(C/F)_{\text{sim}}$ . An emission rate ( $F_{\text{LS}}$ ;  $\text{g s}^{-1}$ ) is then determined after measuring the target gas concentration in the plume ( $C_{\text{obs}}$ ;  $\text{g m}^{-3}$ ):

$$F_{\text{LS}} = C_{\text{obs}}/(C/F)_{\text{sim}} \quad [1]$$

The commercially available software product WindTrax (Thunderbeach Scientific, 2005) was used in this calculation. A global positioning system was used to mark the farm structures, our gas release points (10 points), and the laser paths around the farm. WindTrax determined  $(C/F)_{\text{sim}}$  in one of two modes, depending on how we modeled the emission source. Treated as 10 point sources (the actual configuration), WindTrax calculated 5000 trajectories downwind of each emission point (forward mode). Alternatively, when we treated the farm as two surface area sources, WindTrax calculated 10 000 trajectories upwind of the laser path (backward mode). These sets of trajectories define  $(C/F)_{\text{sim}}$ .

The WindTrax model assumes idealized wind conditions appropriate for simple undisturbed terrain (using Monin–Obukhov wind relationships). However, in our farm setting the buildings and trees created wind complexity. Another difficulty in calculating  $(C/F)_{\text{sim}}$  was that we had to assume an emission source configuration (i.e., location and relative proportion of emissions). While we knew the “synthetic”  $\text{SF}_6$  and  $\text{CH}_4$  release configuration, we did not know the details of the “natural”  $\text{CH}_4$  emissions; this is needed to separate the synthetic from the total emissions. Considering these complications, Flesch et al. (2005) concluded, “with careful selection of a measurement location, an idealized inverse-dispersion technique can give the emissions from a farm complex within an error of  $\pm 10\%$ .” They list three suggestions for dealing with wind and source complexity, and making accurate measurements:

- The farm should be isolated on the landscape, with winds measured in the ambient regime.
- Concentration should be measured at many obstacle heights  $h$  (i.e., barn or tree heights) downwind of the farm (they conservatively propose 20  $h$ ).
- Concentration should be measured at multiple “source-separation” distances  $x_s$  downwind of the farm (distance between separate emission sources, in our case the distance between the barns housing the lactating and the nonlactating cows was 90 m). It is recommended that distances beyond two  $x_s$  be employed.

Our site meets the first condition, but not the last two. At times our concentration measurements were less than 10  $h$  and 1  $x_s$  from the farm. Although the measurement location was closer than recommended, it was chosen to ensure a detectable concentration rise for the  $\text{CH}_4$  lasers.

### Sampling Periods

Our analysis scheme was based on 15-min sampling periods ending at 15, 30, 45, and 60 min past the hour (with corresponding wind measurements). The  $\text{CH}_4$  gas was turned on for 35 min, starting 5 min before a 15-min period, to allow the downwind concentrations to reach equilibrium before the measurement began. At the end of the 35 min the  $\text{CH}_4$  gas was shut off for 25 min. This cycle was repeated each hour (Fig. 2). This on–off release pattern for  $\text{CH}_4$  was adopted to separate the farm  $\text{CH}_4$  emission from the known synthetic emission. After gas release stopped at the end of a 15-min period, we waited for concentrations to fall back to an equilibrium level (typically 5 min) before calculating concentration. From this pattern we created two “gas-on” and two “gas-off” observations each hour. Assuming the natural  $\text{CH}_4$  emissions were constant during the hour, the difference between the gas-on and gas-off emissions was taken as our estimate of the synthetic gas release rate (and should equal the actual  $54.2 \text{ L min}^{-1}$  release rate). Because there were no natural  $\text{SF}_6$  emis-



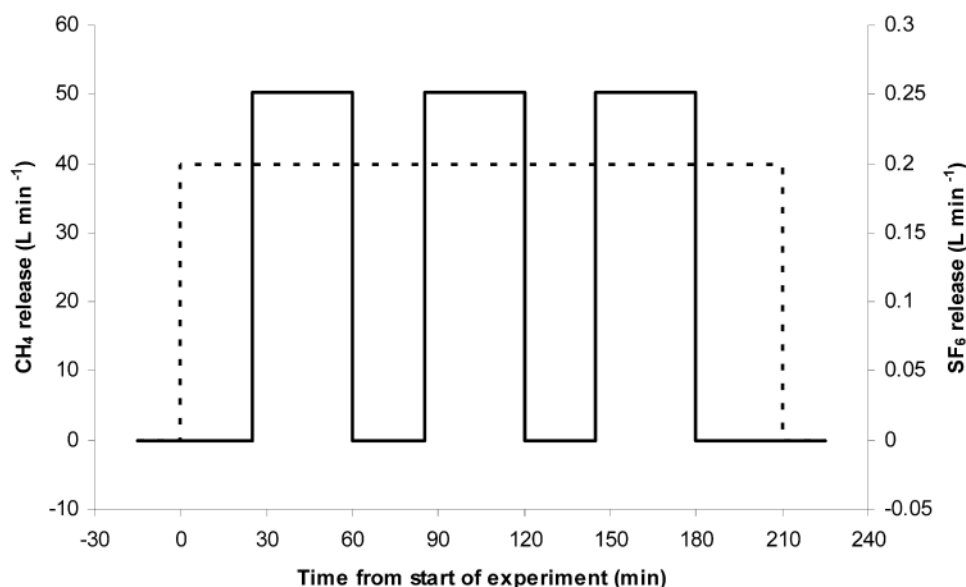


Fig. 2. Illustration of the on-off timing of CH<sub>4</sub> (solid) and SF<sub>6</sub> (dashed) for a sampling period.

sions from the farm, it was not necessary to cycle between gas-on and gas-off conditions. Therefore, the SF<sub>6</sub> gas was left on for the complete measurement period.

During the analysis we ignored some sampling periods. Flesch et al. (2004, 2005) identified conditions when inverse-dispersion calculations are error prone. These include periods when  $u^*$  is less than  $0.15 \text{ m s}^{-1}$ , or the magnitude of the stability length  $|L|$  is less than 10 m (i.e., very stable or unstable atmospheric conditions). Therefore, we ignored data associated with these error-prone periods. Inaccurate results can also occur when concentration is measured at the edge of the plume (Flesch et al., 2005). This occurs when the wind moved the farm plume so that it only “glances” our sampling line. This happened only with our GC line (because it was shorter than the laser line), and we were able to identify these periods visually in WindTrax. We, therefore, ignored those periods when the GC line “sampled” gas from two or fewer of our outlets. The result of this filtering left our experiment with 57 sampling periods for CH<sub>4</sub> (30 gas-on, 27 gas-off), and 41 gas-on periods for SF<sub>6</sub>. These data were collected over 4 d.

## RESULTS AND DISCUSSION

### Concentration Signal

An example of CH<sub>4</sub> concentrations during a release cycle is shown in Fig. 3. There were a number of difficulties encountered using this approach. First, the downwind CH<sub>4</sub> signal results from a combination of natural and synthetic sources. During gas-off periods the concentration was 5 to 10% above the upwind value because of emissions from the cows. During gas-on periods the downwind concentration generally rose by another 5 to 10% because of our synthetic gas additions. Separating the natural and synthetic sources was problematic because of the likelihood of differences in the two source configurations. Here we assumed the configuration of natural CH<sub>4</sub> emissions was identical to the synthetic. To get the synthetic emission rate we subtracted the gas-off emissions from the gas-on values, and assumed the natural emissions were the same for both groups. This

may not be true if the natural emissions changed with time. This possibility was reduced, however, by our use of short, alternating gas-on and gas-off periods (30 min). This difficulty does not exist for SF<sub>6</sub>.

Another difficulty was that when the gas was turned on the downwind concentration rose, but the increase was not a step-change; rather a slow ramp-up occurred. In the second gas-on cycle in Fig. 3, it is difficult to determine whether an equilibrium concentration was attained (our assumption was that equilibrium occurred 5 min after the gas was turned on). The downwind concentration signal was quite variable, in part due to gas being entrained and stored in the large milking barn, then later flushed out. This “storage” capability makes our 15-min analysis periods inadvisably short, and our emission estimates noisy. This finding meant it was important to focus on the daily average recovery rates, not the noisy individual 15-min values. As a result, all the gas-on data for the day were averaged and then the daily average gas-off value was subtracted. The variability attributed to store, plus other variability attributed to changes in wind direction, would also impact the downwind SF<sub>6</sub> concentration measurement.

### Gas Recovery Using the Actual Source Configuration

In the following discussion we judge the success of our inverse-dispersion calculations in terms of recovery rate, which expresses the inferred emission rate as a percentage of the known release rate. When we treat our farm emissions as coming from 10 point sources, using the actual outlet locations (including the height of release) in WindTrax, the average recovery rate for CH<sub>4</sub> was 86% (Table 1). More impressive was the 91, 105, and 89% recovery on three of the four days. The cause of the larger error of 59% recovery rate on 1 December was not identified. In terms of wind conditions, there was nothing dramatically different on this

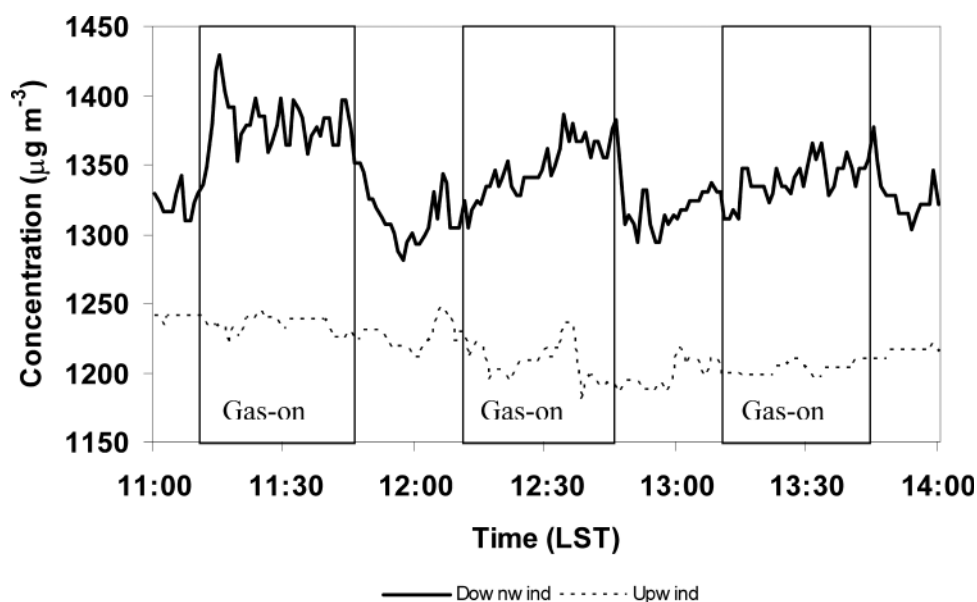


Fig. 3. Example of the time series of line-average methane concentration ( $C_L$ ) taken upwind and downwind of the farm on 9 November.

Table 1. Methane and tracer gas recovery rates from inverse-dispersion calculations. We assumed the emission configuration was the actual 10 point sources constructed for the experiment. The difference between methane “gas-on” and “gas-off” emission rates should match the amount released at the farm.

Date, 2004	Methane gas				Tracer gas	
	Gas-off	Gas-on	Difference	Recovery	Gas-on	Recovery
		$\text{g d}^{-1}$		%	$\text{g d}^{-1}$	%
9 Nov.	95 655	141 329	45 674	91	2659	148†
1 Dec.	99 307	128 707	29 400	59	1339	74
9 Dec.	90 813	143 167	52 354	105	1760	98
10 Dec.	80 924	125 396	44 472	89	1408	78
Average	91 675		42 975	86	1792	100
SD	6 900		8 393	17	526	29

† Coincides with a short sampling line.

day. On average the  $\text{SF}_6$  results were better, with a perfect recovery of 100% ( $\pm 29\%$ ; Table 1). The better recovery for  $\text{SF}_6$  compared with  $\text{CH}_4$  was expected, since we did not have to deal with confounding natural emissions.

We conclude that our inverse-dispersion technique accurately measured the synthetic emissions. This was surprising given how close our concentration measurements were to the farm. At the nearest point, our measurement fetch was  $9h$  (where  $h$  is the barn height). This is much closer than the  $20h$  suggested by Flesch et al. (2005). It follows that for our design, despite the possible wind disturbance from the farm buildings, we were able to demonstrate our dispersion calculations were valid.

The perfect average recovery of  $\text{SF}_6$  hides a large day-to-day variability, from 148% on 9 November to 74% on 1 December. This large variability (compared with  $\text{CH}_4$ ) may be partially due to the short sampling line. While the  $\text{CH}_4$  concentration path length was between 250 and 360 m, and positioned so that the downwind laser usually captured the full width of the farm emission plume, the  $\text{SF}_6$  line was only 100 to 200 m long, which was not long enough to capture the full plume. This increases the uncertainty in our calculations, as the  $\text{SF}_6$  concentration along the sampling line would be sensitive

to lateral dispersion from the farm (whereas if the sample line spans the plume it is insensitive to lateral dispersion). Likewise, our calculated  $F_{LS}$  would be similarly sensitive to the modeled dispersion. This is an important consideration, as modeling horizontal dispersion is more error prone than modeling vertical dispersion (Flesch and Wilson, 2005).

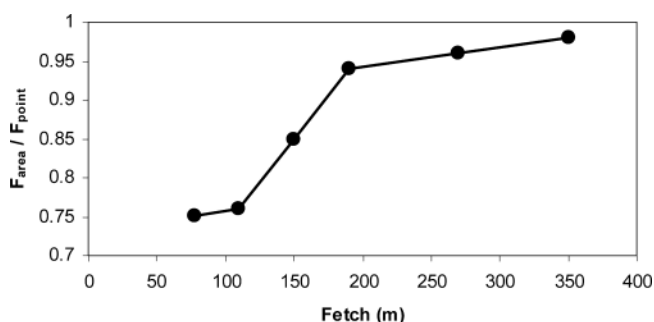
Inadequate sampling may also cause some of the  $\text{SF}_6$  uncertainty. From Fig. 3 we can see the strong temporal variability in  $\text{CH}_4$  concentration, which also exists for  $\text{SF}_6$ . Given this variability, our  $\text{SF}_6$  sampling frequency of once every 5 min may be insufficient to give an accurate 15-min average (to correspond with the 15-min wind statistics).

### Gas Recovery Using a Generic Source Configuration

In theory, accurate inverse-dispersion calculations require that we model the actual emission source configuration. In many real-world situations we do not have the privilege of knowing these details. For example, we do not know the proportion of natural  $\text{CH}_4$  emissions coming from the barn and the dry stock pens. Flesch et al. (2005) discussed a solution to this problem: locate the concentration measurements where the modeled

**Table 2. Methane and tracer gas recovery rates from inverse-dispersion calculations. We assumed the emission configuration was two surface area sources (area covered by the milking and dry barns). The difference between methane “gas-on” and “gas-off” emissions should match the amount released at the farm.**

Date, 2004	Methane gas				Tracer gas	
	Gas-off	Gas-on	Difference	Recovery	Gas-on	Recovery
		$\text{g d}^{-1}$		%	$\text{g d}^{-1}$	%
9 Nov.	70 898	111 443	40 545	81	2197	122
1 Dec.	77 567	99 767	22 200	44	1066	59
9 Dec.	68 500	105 603	37 103	74	1353	75
10 Dec.	51 207	84 141	32 934	66	927	52
Average	67 043		33 196	66	1386	77
SD	9 728		6 897	14	493	27



**Fig. 4. Hypothetical ratio of emissions calculated using a source configuration of 10 point sources with that using two area sources ( $F_{\text{area}}/F_{\text{point}}$ ), plotted versus distance from the farm boundary to the line-average concentration measurement (fetch).**

$(C/F)_{\text{sim}}$  will be insensitive to the source configuration details. Generally, this sensitivity is reduced as we move downwind. Our dataset allows us to consider the problem of unknown source configuration, and how it influences inverse-dispersion calculations.

As a hypothetical exercise, we applied the inverse-dispersion technique to our farm, but now assume a generic emission configuration. From a distance we might broadly identify two emission sources: the milking barn and the dry stock pens (i.e., where the cattle are). In WindTrax we thus treat the farm as two surface sources, corresponding to the barn and pens, and assume each has the same real emission rate. Although this does not match either the natural or synthetic source configuration, it has obvious similarities in terms of the relative spread of release, and is a rational choice given limited information. The question is how much this assumption affects the emission calculations.

We recalculated the  $\text{CH}_4$  and  $\text{SF}_6$  recoveries using WindTrax with the generic configuration (Table 2). Not surprisingly, there was a decline in accuracy. We found the average  $\text{CH}_4$  recovery was reduced from 86 to 66%, and  $\text{SF}_6$  recovery from 100 to 77%. From Flesch et al. (2005) we conclude that this undesired sensitivity is the result of concentration being measured too close to the farm.

Using WindTrax we examined how measurement fetch influences the sensitivity to source configuration. Taking the two configurations used here (10 points vs. two area sources), we calculated a ratio of the resulting emission estimates ( $F_{\text{area}}/F_{\text{point}}$ ) to determine how this ratio changes with fetch. We used concentration data from a north-south oriented laser path, positioned east of the farm, and westerly winds and neutral atmospheric stability. Figure 4 shows how  $F_{\text{area}}/F_{\text{point}}$  changes with distance from the

farm. When the laser is 80 m east of the farm (approximating our actual positioning), then  $F_{\text{area}}/F_{\text{point}}$  is about 0.75. But, beyond about 175 m the difference drops to less than 10%. It follows that if the source configuration at 1 an actual farm is uncertain, then the concentration measurements should be moved as far downwind as practically possible. A major limitation of measuring far downwind is the ability to resolve differences between up- and downwind concentrations (e.g., lower concentrations at longer distances from the source approach upwind concentrations and require highly precise measurements to determine the difference). In addition, it is recognized that any error in determining the size of the dispersion plume will grow as the distance from the source increases. In our study, Fig. 4 coincides with the recommendation from Flesch et al. (2005), that one should move beyond about  $2x_s$  (i.e., 180 m) to reduce the sensitivity of emission calculations to source configuration details. Although if the farm emission configuration is treated even more crudely, such as a single point source, then even more distance would be required.

## Enteric Methane Emission Values

The  $\text{CH}_4$  emission rate calculated for the gas-off intervals (Table 1) should reflect the whole-farm  $\text{CH}_4$  loss (excluding the manure storage facility). Expressing the average off-time emissions ( $91\,675\text{ g d}^{-1}$  in Table 1) on an individual animal basis yields  $286 (\pm 22)\text{ g d}^{-1}\text{ animal}^{-1}$ . Kinsman et al. (1995) estimated that for a large lactating dairy herd, the average enteric  $\text{CH}_4$  emission was  $400 (\pm 42)\text{ g d}^{-1}\text{ cow}^{-1}$  (using a conversion factor of  $1470\text{ kg CH}_4\text{ L}^{-1}\text{ CH}_4$ ). A nonlactating cow is reported to emit about half the enteric  $\text{CH}_4$  relative to a lactating cow (Marik and Levin, 1996). Weighting these two emissions by the fractions of lactating ( $152/321$ ) and nonlactating ( $169/321$ ) animals in our study, yields an expected emission of  $294\text{ g d}^{-1}\text{ cow}^{-1}$ . This is very similar to our measured emission of  $286\text{ g d}^{-1}\text{ cow}^{-1}$  in our study.

## CONCLUSIONS

We found that inverse-dispersion calculations gave gas emissions from a dairy farm with reasonable accuracy. On average we “recovered” our synthetic gas emissions of  $\text{CH}_4$  and  $\text{SF}_6$  to within 15%. As a further indication of success, “natural”  $\text{CH}_4$  emissions were calculated to be  $286\text{ g d}^{-1}\text{ animal}^{-1}$ , almost identical to that derived from previous studies. Our results are strong evidence

that an idealized inverse-dispersion technique that ignores wind complexity can be used for some real-world settings. In applying this technique, it is advisable to first show this is a valid assumption, using a release-recovery study as in our study.

Several factors were important to our successful application. First, the farm studied was relatively isolated on the landscape. This meant a clearly defined ambient wind regime, and locating our anemometer in this regime was straightforward. It also meant that we did not have other nearby emission sources (for CH<sub>4</sub>) to confound our concentration signals. A second factor was that we used relatively long line-average concentration measurements. The advantage of this should not be ignored. As argued by Flesch and Wilson (2005), utilizing crosswind average concentration reduces one of the major sources of uncertainty in the inverse-dispersion technique, specifically inaccurate modeling of lateral dispersion. Another factor in our success was ignoring periods known to be problematic for inverse-dispersion calculations (i.e., low winds, extreme stabilities, and measurements of downwind concentration that do not sample enough of the farm plume). One difficulty is the tracking of trajectories when wind directions are not consistent over the averaging time, common under low winds and very stable periods. Shortening the averaging time may avoid this particular problem in the inverse-dispersion calculation.

A fourth factor in our success was having a concentration measurement location that allowed us to ignore wind complexity. Even though we were as close as 75 m to the farm, this was evidently far enough (and much closer than recommended by Flesch et al., 2005). But to achieve accurate results at this location, it was necessary to use the actual source configuration in the dispersion calculations (i.e., 10 outlets). In many real-world situations these details will not be known, requiring assumptions about the source configuration. This will mean locating the measurement location further from the farm, keeping in mind that the location is a compromise between being far enough from the source to ensure the plume is uniform, yet close enough to ensure the target gas concentration is detectable above background concentration.

The selection of a proper concentration measurement location is probably the foremost issue in applying the inverse-dispersion technique. Concentration must be sufficiently high (relative to background) for accurate detection with the measuring devices. This creates a

tension between wanting to be close to better detect concentration rise, and wanting to be far to minimize dispersion modeling errors caused by wind and source complexity. Our results highlight how the accuracy of the modeled source configuration can influence this distance decision. We conclude that the more one knows the source geometry and their relative strengths (e.g., the relative location, size, and type of animals, barn construction), and incorporating these to give an accurate source configuration in the dispersion model, the greater the likelihood of a successful application.

#### ACKNOWLEDGMENTS

This study was funded by National Carbon and Greenhouse Gas Emission Accounting System (NCGAVS) and the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS). Technical support for the study was provided by Trevor Coates, Nathan Dyck, Linda Kremenik, Darrell Vedres, and Jason Seabrook at Agriculture and Agri-Food Canada's Lethbridge Research Centre.

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